# THE AGE AND CONTEMPORARY ENVIRONMENTS OF TOWER HILL VOLCANO, SOUTHWEST VICTORIA, AUSTRALIA

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Tower Hill ash forms a useful chronological marker for archaeological and geological sites in the Warrnambool-Port Fairy area. The current paper establishes an age of 35 ± 3 ka for the eruption of Tower Hill. Confidence in this age is provided by the agreement of results from three dating techniques on different types of material – accelerator mass spectrometry (AMS) radiocarbon dating of lake core sediments in a crater of the volcano, conventional radiocarbon dating of plant remains in a palaeosol buried by volcanic ash and thermoluminescence dating of quartz grains in a sand covered by the ash. Palynological analysis of lake sediment indicates the presence of a steppe-type vegetation at the time for which no present day analogue exists in Australia

*Keywords:* radiocarbon, thermoluminescence, palynology, pollen, lake sediments, geochronology

TOWER Hill volcano (38°19'S, 142°22'E) lies towards the southwestern extremity of the extensive volcanic plain of western Victoria and within a few km of the coast (Fig. 1). It is a maar volcano with nested scoria cones (Orth and King 1990). Ash from the volcano covers 150km$^2$, with deposits being found up to 20km away. The crater itself has a maximum diameter of 3.2km and the northeast crater rim is 110m above the present floor (Orth and King 1990). Prior to the arrival of European people, the surrounding plains were covered in *Eucalyptus*-Casuarinaceae woodland and grassland, with open forest occurring on Newer Volcanic deposits such as those of Tower Hill. The site experiences a warm temperate climate with a mean annual temperature of almost 14°C and a mean annual rainfall of about 750 mm with a winter maximum.

As its name suggests, Tower Hill volcano is a prominent physiographic feature of the predominantly flat southwest Victorian coast (Gill 1978). Its well-preserved geological features were suggestive to earlier investigators of a young eruption age (of the order of 1000 years; Gill 1953). Subsequent research, reviewed by Head et al. (1991), has suggested progressively greater ages for the volcano. It appeared that volcanic activity was older than 20ka, based on radiocarbon dating of material obtained from cores in lake sediments of the volcano. Since lake sediments must have formed some time after the cessation of volcanic activity they indicate a minimum age for the eruption.

Several authors have discussed the value of reliable ages for the eruption of Tower Hill and other western Victorian volcanoes (Coutts 1981; Head et al. 1991; D'Costa et al. 1989). Ash from the volcano forms a useful chronological marker for archaeological and geological sites in the Warrnambool-Port Fairy area. We report here the results of three recent independent determinations of the age of the Tower Hill eruption which are consistent with an eruption of ~35 ± 3ka. The agreement between the dating techniques gives confidence in the assigned age because of the different materials and methodologies involved (Sherwood et al. 1994).

The three methods utilised by us were:

i) Accelerator mass spectrometry radio-carbon dating of material from the basal material of a lake sediment core taken within the Tower Hill crater complex

ii) Thermoluminescence dating of quartz grains from a calcarenite sand underlying Tower Hill Tuff at Thunder Point (approximately 13km SE of the eruption centre)

iii) Conventional radiocarbon dating of woody plant material preserved beneath the original land surface and uncovered during quarry operations in Tower Hill Tuff at Davison's quarry (approximately 1.5km east of the crater).

## SITE DESCRIPTION AND METHODS

### *Radiocarbon dating of Northwest Crater lake sediments*

Oldest radiocarbon ages obtained previously from Tower Hill sediments were from the base of a 15.5 m core extracted from the centre of Northwest Crater, contained within the scoria cone complex within the Tower Hill maar (Fig. 1). The conventional radiocarbon ages of 18,330 ± 260 yrs BP (Beta-16156) and 23,260±2540 yrs BP (Beta-16155) were obtained from organic and carbonate fractions of submitted bulk sediments. It was considered that the carbonate fraction age could be too old because of likely incorporation of Tertiary limestone derived from underlying country rock during the volcanic explosions.

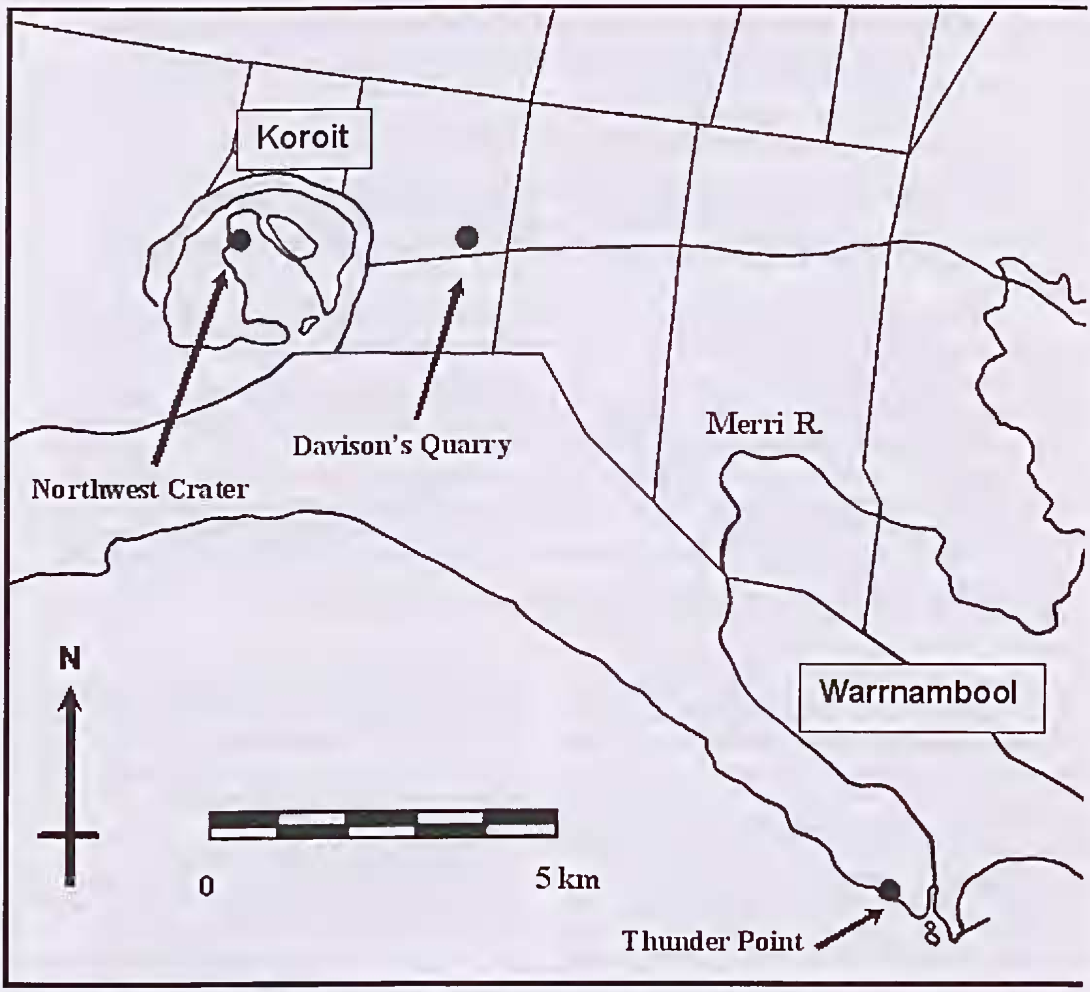


*Fig. 1.* Locality map for Tower Hill showing Thunder Point and Davison's Quarry.

In recognition of this possibility, extrapolation from younger radiocarbon dates within the sequence was used to estimate the most likely age as *ca* 21,000 yrs BP (D'Costa et al. 1989).

Coring of Northwest Crater was terminated at 15.5m rather than reaching the base of the lake and swamp sediments because of the difficulty of penetrating further using hand-operated equipment. As the site was not accessible to a drilling rig, further sediment collection had to await the design and acquisition of a lightweight mechanical core sampler. Such a sampler, operated by hydraulics, was available for use in 1997. The sampler was attached to a constructed platform in the centre of the crater and cores were extracted, in metre lengths, to a depth of 23.0 m. As the core bottomed in scoria, it was assumed that the total depth of accumulated lake sediment had been sampled.

The lowermost lake sediment was prepared for radiocarbon dating in a similar manner to that for pollen analysis to remove calcium carbonate and other possible contaminants such as mobile organic constituents that might effect a radiocarbon date. The prepared sample was then radiocarbon dated by accelerator mass spectrometry at the University of Waikato, New Zealand. A second sample from the same depth was prepared for pollen analysis to provide some biostratigraphic check on the radiocarbon age and to provide background information on conditions existing at the time of eruption. Preparation of both samples followed standard procedures detailed in Moore and Webb (1978) and included hydrochloric acid and hydrofluoric acid treatments as well as acetolysis.

### *Thermoluminescence (TL) dating of sand at Thunder Point*

TL dating of calcareous sediments in the Warrnambool region has identified major dune building episodes at approximately 500ka, 330ka, 240ka, 200ka, the last Interglacial and the Holocene (Oyston 1996). As part of this research, an interbedded sequence of five aeolianites (coded WTPA) and four palaeosols (coded WTPS) was studied at Thunder Point (Fig. 2). The topmost aeolianite (WTPA5) is a thin sand layer overlain by Tower Hill tuff and lies on top of a distinctive well-developed sandy clay loam (WTPS4), which is unlike any other soils in the sequence.

Samples were collected by augering, taking care to avoid exposing the samples to light. At the same time samples were also taken for moisture and analysis of isotopes of uranium, thorium and potassium – concentrations of these elements being needed to calculate annual dose rates from in-situ radiation. A small contribution is also made by cosmic rays (Smith & Prescott 1987).

TL analysis was conducted on the quartz grains isolated from the calcareous matrix using the total bleach, Australian slide method. Testing of the effectiveness of sunlight bleaching on modern surface samples suggests the total bleach model is appropriate for buried dune samples up to 70ka. The method is more fully described elsewhere (Smith and Prescott, 1987; Sherwood et al. 1994; Oyston, 1996)

The dose rate for TL ages from Thunder Point was determined by alpha counting of material sampled to obtain TL equivalent dose. Given that the TL ages are in general agreement with their stratigraphic position, it is considered that a change. in dose rate due to the influence of adjacent stratigraphic sediment/soil/tuff layers is likely to be insignificant in relation to the errors in the ages.

The soil horizons at Thunder Point were found to have very similar dose rates to the intervening sand layers and so would not change the dose rate calculation significantly. The thin layer of tuff was more than 30 cm from the edge of the sample collection tube. It is considered that this distance would significantly reduce the influence of the tuff on the dose rate in the underlying sand.

It is acknowledged that ideally in-situ dosimetry would be a preferable means of obtaining a dose rate for the Thunder Point sediments, but this technique was not undertaken in this case.

### *Radiocarbon dating of plant material from Davison's Quarry*

Excavation of tuff to a quarry depth of approximately 20m below the present surface revealed the original (pre-eruption) land surface. This consists of a grey soil overlying a yellow-grey mottled clay containing buckshot nodules and large (up to ~0.5m diameter) rounded basalt boulders. The palaeosurface grey soil was quite lithified where sampled and large slabs (up to 1m across) remained intact when lifted. The quarry owner (Mr G. Davison) kindly excavated fresh material and two samples of plant material were collected by breaking up the grey palaeosol.

Sample A was a single piece of dense dark brown timber found in the palaeosol directly beneath the tuff layer, while sample B was composed of brown, cylindrical spongy roots (or rhizomes), of varying diameter up to 1 cm, located commonly about 10cm below the tuff layer in the palaeosol. Sample B was collected approximately 10m east of sample A.

The plant specimens were hand-sorted from fragments of tuff and other debris and dried at 105°C for 6 hours. The dried samples (A – 26.39g; B – 11.08g) were sent to the University of Waikato Radiocarbon Dating Laboratory. There the samples were scraped clean, chopped into fine splinters and milled. After washing with distilled water, they were dried prior to a series of washings that included hot 10% hydrochloric acid, distilled water and hot 5% sodium hydroxide. The sodium hydroxide insoluble fraction was treated again with hot 10% hydrochloric acid, filtered, rinsed with distilled water and dried prior to carbon -14 radiometric analysis.

### *Calibration of radiocarbon dates*

Conventional radiocarbon ages, related directly to the dating of the Tower Hill eruption, have been calibrated to calender years using the Nordic Sea record (Voelker et al. 2000), generally believed to be the most reliable of the available calibration datasets beyond 20,000 yrs BP (Laj et al., 2002). Calibration was undertaken to provide direct comparison with the TL age.

## RESULTS

### *Samples from Northwest Crater, Tower Hill*

The radiocarbon age from the base of the Northwest Crater sequence is shown in Table 1 while its relationship to other ages found for this site and a core from the main lake surrounding the scoria complex is shown on Fig. 3. There is good agreement between ages from Northwest Crater and the Main Lake sediments back to the base of cored sediments at Main Lake dated to 11,550 years BP. The continuation of the linear age-depth line through the Northwest Crater age of 18,330 yrs BP was considered unrealistic by D'Costa et al.

| Site | Sample | Code | Uncalibrated (yrs BP) | Calibrated (yrs BP) |
|---|---|---|---|---|
| Northwest Crater | NWC (97) 22.10 m | Wk-6012 | 29,720 ± 290 | 34,600 ± 400 |
| Davison's Quarry | A | Wk-7446 | 32,900 ± 430* | 37,400 ± 1,000 |
| | B | Wk-7447 | 32,990 ± 590* | |

*Table 1.* Calibrated and uncalibrated radiocarbon dates for basal lake sediments from Northwest Crater, Tower Hill and plant remains from Davison's Quarry.

* error is 1 standard deviation and is based on counting uncertainties.

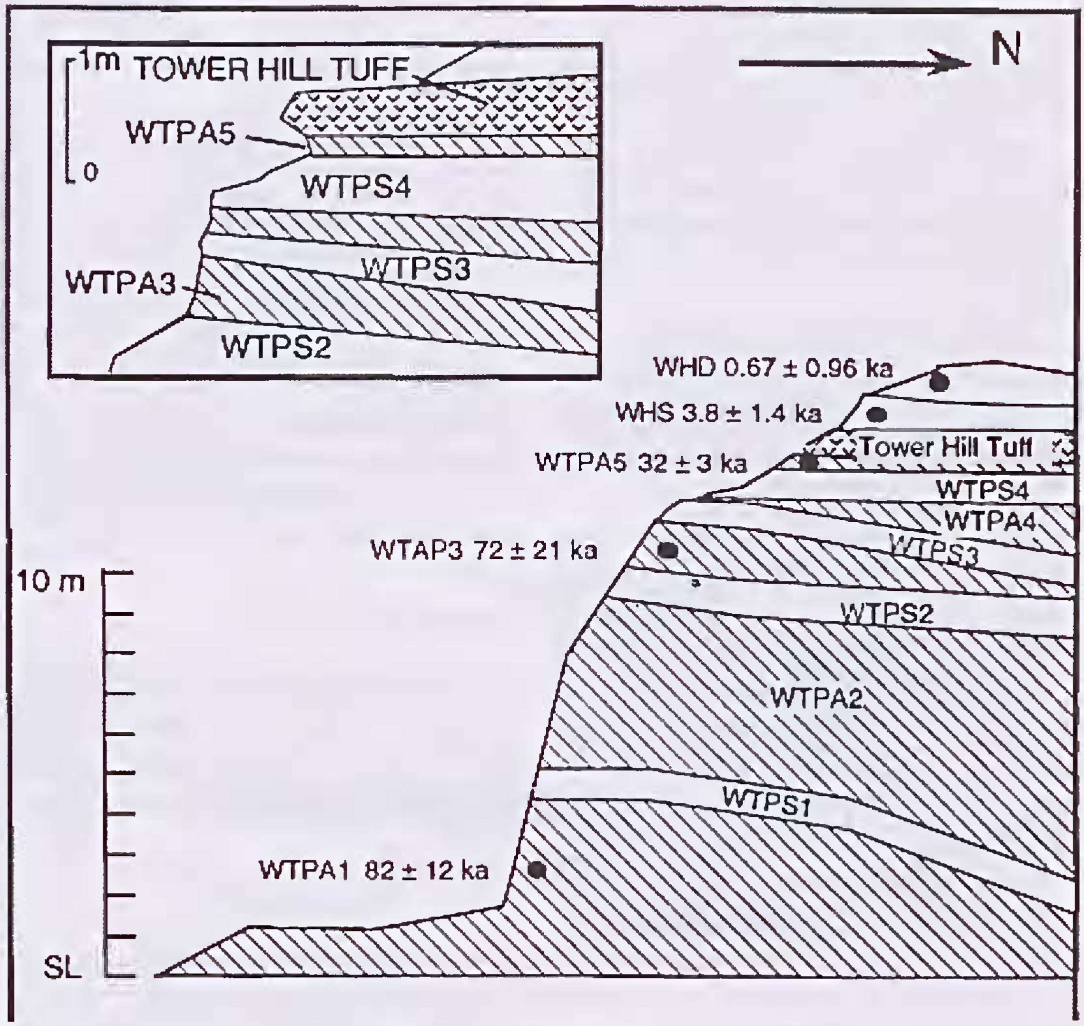


*Fig. 2.* Cliff section at Thunder Point, Warrnambool, showing the sequence of sedimentary layers dated and their TL ages

(1989) as there were signs of lake drying during the late glacial period (15,000 to 10,000 yrs BP) in line with dry conditions recorded elsewhere in Australia at this time (Kershaw and Nanson 1993). Continuation of this line would also suggest a significantly younger age than 29,720 yrs BP (34,600 calibrated yrs BP) for the base of the sediments. The acceptance of the age of 15,100 yrs BP is consistent with a reduction in the average rate of sediment accumulation during the late glacial period. Of the optional age-depth lines considered by D'Costa et al. (1989) beyond this time, option C was preferred on the grounds that sediment accumulation appeared to be continuous again before the late glacial period and would most likely have been similar to that of the Holocene. The continuation of this line to the base of sediments results in an age very similar to that reported here.

The pollen assemblage associated with the basal age is dominated by terrestrial taxa of which the Poaceae and Asteraceae are by far the most important with 37 and 41% of the dry land pollen sum respectively. The Chenopodiaceae also have notable representation (11%). All woody plants have low values except for *Banksia* (13%) but the present dominant trees of regional vegetation, *Eucalyptus* and Casuarinaceae, each have less than 3% of the pollen sum. Aquatic pollen are relatively sparse and are derived predominantly from the shallow water taxa *Myriophyllum* spp. and *Myriophyllum muelleri*, the latter species suggesting also brackish water conditions. High charcoal levels suggest frequent or intensive burning within the catchment.

These pollen data, like the radiocarbon age, are generally consistent with a last glacial age for the sample (Kershaw et al. 1991). However, the dry land pollen indicate a vegetation cover as extreme, in terms of reduced tree cover, as that during the Last Glacial Maximum (Stage 2) which is considered not to have commenced until about 29 ka, according to the marine oxygen isotope stratigraphy (Martinson et al. 1987). Although the statistical range around the conventional radiocarbon age could almost allow it to be fitted into Stage 2, the calibrated radiocarbon age predates this by 4 to 5 thousand years (Voelker et al. 2000). The lack of a continuous, dated pollen record through the Late Pleistocene from any site in southeastern Australia prevents further assessment of the validity of the sample age based on pollen stratigraphy.

*Thunder Point*

Figure 2 gives the TL ages for five units exposed in the cliff section at Thunder Point. The sediment ages form a consistent progression from the oldest unit at the base of the sequence to the youngest at the surface. The basal aeolianite continues below sea level, indicating it was formed during a period of lower sea level. Its TL age indicates a late Last Interglacial (LIG) formation, possibly marine isotope substage 5.0 or 5.1 of Martinson et al. (1987).

The last bleaching of the quartz in sample WTPA5 occurred after this dune-building period and prior to the Last Glacial maximum. A younger age for this aeolianite is consistent with the distinctively different appearance of the undated soil (WTPS4) underlying WTPA5. The appearance of this strongly leached leptic tenosol suggests different climatic conditions existed during its formation to those which formed the poorly developed palaeosols within the LIG dune. For the unit WTP5, the equivalent dose (D) of 20.6 ± 0.9 Gy, and the dose rate (DR) of 0.639 ± 0.036 Gy/ka gives a maximum age for the Tower Hill eruption of 32±3ka. The TL age of 0.67 ± 0.96ka for the uppermost unit (sample WHD) was obtained for an active modern calcarenite dune and is effectively zero demonstrating the effectiveness of solar bleaching at this location.

*Davison's Quarry Site*

Radiocarbon ages for the two plant specimens are given in Table 1. The agreement between the two determinations, based on two types of plant material located 10m apart, is excellent. The range of possible conventional radiocarbon ages indicated by the quoted uncertainties and based on a C14 half-life of 5568yrs (corrected for isotopic fractionation) is 32.5 – 33.6 ka. Based on this the calibrated radiocarbon age is 37.4 ± 1.0 ka BP.

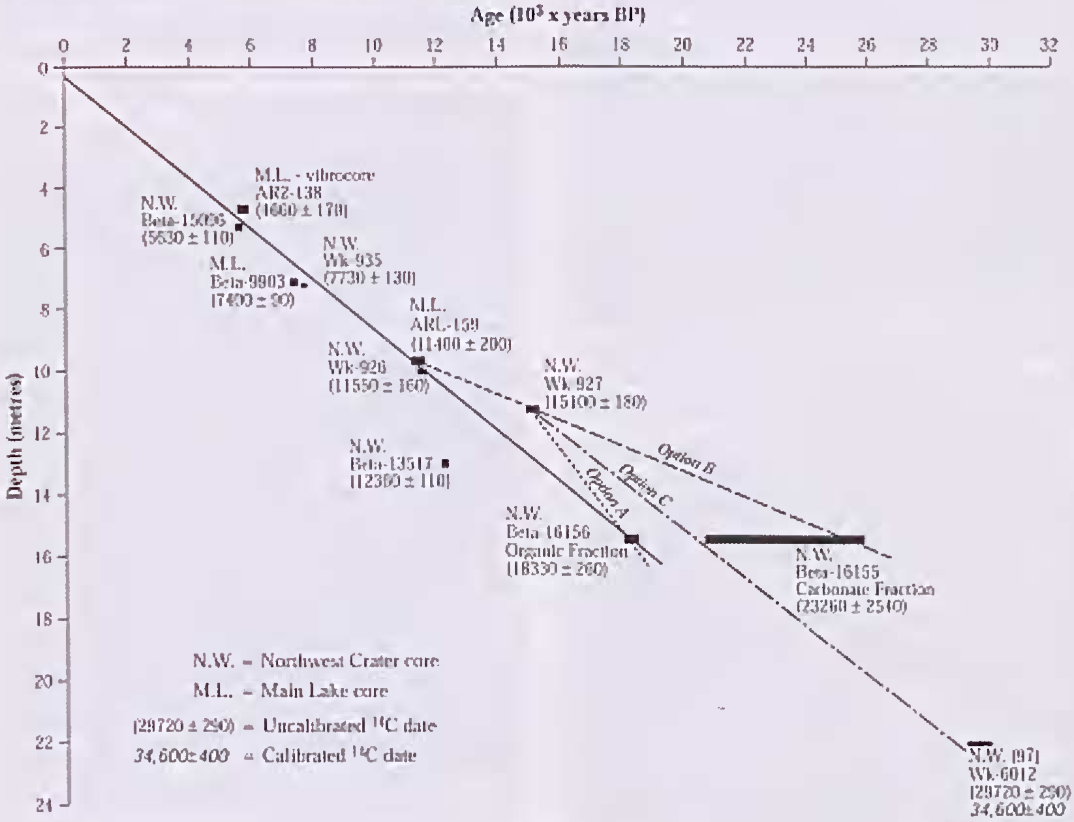


*Fig. 3.* Possible age-depth lines for sediment accumulation at sites from Tower Hill (modified from D'Costa et al. 1991)

| Volcano | Age (ka BP) | Dating Techniques | Reference |
|---|---|---|---|
| Mt Schank (SA) | < 18.1 ± 0.35 | C14⁺ | Polach et al. 1978 |
| | 4.93 ± 0.54 | TL | Smith & Prescott 1987 |
| Mt Gambier (SA) | ~4.3 | C14 | Blackburn et al. 1982 |
| | > 28 | C14⁺ | Leaney et al. 1995 |
| Mt Eccles (Vic) | < 19.3 | C14⁺ | Gill 1980 |
| | 28 – 32* | C14⁺, Cl36* | Head et al. 1991, Ollier 1981, Stone et al. 1997 |
| Tower Hill (Vic) | 35 ± 3 | C14, TL | This Study |
| Mt Napier (Vic) | 31.9 ± 2.4 | Cl36 | Stone et al. 1997 |
| Mt Porndon | 58.5 ± 5.0 | Cl36 | Stone et al. 1997 |

*Table 2.* Determinations of the eruption date for younger volcanoes in the Newer Basalt field
* Upper limit for age inferred from Cl - 36 dating of Mt Napier eruption.
⁺ Uncalibrated ages, perhaps 3-4ka below the calibrated age.

## DISCUSSION

### *Concordance of age determinations*

Before discussing the concordance of the different age determinations, it is important to consider which event is being dated with each method. Both the radiocarbon dating of vegetation at Davison's Quarry and TL dating of sand at Thunder Point estimate a time pre-dating the eruption. Blanketing of the land surface by volcanic ash during eruption isolated its vegetation from the atmosphere and blocked sunlight from quartz grains. Dating of material in lake sediments should give ages that post-date the cessation of volcanic activity by an unknown period (the time for a lake to form after the final phase of scoria cone formation and then for sedimentation to commence). It should also be noted that, given the large uncertainties associated with each determination (up to 3ka), it may not be possible to resolve the times of commencement and conclusion of volcanic activity. It has been estimated, for instance, that the Tower Hill volcano could have been constructed within a few years and possibly even a few months (Orth and King 1990).

Despite these qualifications, however, the results of this investigation have given generally consistent ages for the Tower Hill eruption. The TL age for Thunder Point (32 ± 3ka) overlaps the calibrated C14 age from Northwest Crater (34.6 ± 0.4ka) based on the experimental uncertainties. The calibrated C14 ages for Davison's Quarry (37.4 ± 1.0ka) and Northwest Crater do not overlap but the date from the lake sediment is younger than that from the quarry, consistent with the sequence of eruption events. The apparent lack of any discontinuity between the scoria and base of organic sedimentation in the Northwest Crater core suggests that sedimentation began soon after the formation of the crater within the scoria cone. As the water levels in Tower Hill are controlled by ground water, there would be no requirement for basins to fill with rainwater before sedimentation commenced. If this argument is sound, the major factor contributing to the age gap between dates could be the elapsed time between initial maar formation and subsequent scoria cone activity i.e. two events of relatively short duration separated by a longer interval.

A mean eruption age, based on all three determinations is 35 ± 3ka. The uncertainty is calculated as the root mean square of the uncertainties quoted for each determination.

### *Palaeoecological considerations*

The eruption of Tower Hill occurred just before the Last Glacial Maximum at a time when sea level was 80-90m lower than present. At this time the coast would have been at least 30km south of its present position and the volcano well inland as a consequence. Pollen analysis indicates a regional cover of steppe-type vegetation for which there is no present day analogue in Australia. In other parts of the world, steppe is associated with dry, cool conditions and these are consistent with most available evidence for the last glacial period in southeastern Australia (Kershaw 1998). It is difficult to imagine, however, temperatures and precipitation sufficiently extreme to exclude sclerophyll woodland or forest, considering the broad climatic adaptation of this type of vegetation. In addition, the presence of extensive *Banksia* around the site, probably shrubby *Banksia marginata*, as well as the regional survival of both sclerophyll forest and rainforest vegetation in the nearby Otway Ranges (McKenzie & Kershaw 2000), would suggest that temperatures were not too low to exclude trees from the area. Similarly, the fact that a lake could form within Tower Hill suggests that precipitation was not too low to exclude trees. In fact, considering the impact of lowered ground water with the marine regression, it is likely that effective precipitation was not much different to that of today. Consequently other factors, such as altered seasonality, extreme climatic events and the lowered concentration of $CO_2$ in the atmosphere during the last glacial period, have to be considered in an explanation of the landscape at the time of eruption.

One significant aspect of the vegetation preserved in Davison's quarry was its remarkably fresh appearance. Maar volcano eruptions are described as phraetomagmatic – explosive eruptions due to the combination of magmatic gases and steam derived from ground or surface waters (Joyce 1988). Basal surges accompanying these eruptions can travel at high speed and be highly destructive (Orth & King 1990). Cross-bedding in tuff around Tower Hill is evidence of such surges. It is possible that such violent events occurred later in the eruption and that initial phases were less violent. This is supported by observations during excavations to collect C14 samples. An intact clump of a sedge species and tuff-coated casts of grass stems were observed on the original ground surface. Burial of the original ground surface, apparently under low energy conditions, protected the buried vegetation from destruction during later, more violent eruptive episodes.

Ollier (1981) found a soil preserved in similar circumstances at the base of a quarry in volcanic tuff and scoria at Mt Eccles, approximately 80km northwest of Tower Hill. He collected small roots (up to 1mm in diameter) from the Mt Eccles palaeosol for radiocarbon dating. Similar small roots were common in the soil at Davison's Quarry but these were not used for dating purposes. Ollier (1981) also identified pollen from various taxa, predominantly Asteraceae, but with some *Casuarina, Eucalyptus*, grasses, *Grevillea, Haloragis, Beyeria* and fern spores. The excellent preservation of such plant remains suggested to Ollier that volcanic deposition was hot enough to kill microorganisms capable of decomposing organic matter but not hot enough to char the latter. Observations at Davison's Quarry are consistent with this hypothesis. Given this, it is possible that a detailed survey of vegetation and pollen preserved below volcanic deposits at such sites could provide valuable evidence for the nature of western Victoria's vegetation assemblages at the time of volcanic eruptions. This research could substantially refine reconstructions presently based on palynological studies of lake sediments.

Radiocarbon dating of the roots collected at Mt Eccles gave an uncalibrated age of 28,750 +11,700 /-4,600 yrs BP (Ollier 1981). This age was significantly greater than other eruption ages based on radiocarbon dating of peats supposedly formed when lava flows from Mt Eccles blocked drainage of nearby streams (Gill 1978; Gill 1980). Subsequently, Head et al. (1991) obtained an uncalibrated radiocarbon age for basal peat in Whittlebury Swamp of 27,510 ± 240 yrs BP, and in Condah Swamp of 26,240 ± 480 yrs BP. These authors argued that earlier, younger dates were based on peats formed well after drainage was first blocked. The agreement between radiocarbon ages for fossil vegetation and other techniques at Mt Eccles and Tower Hill suggests plant material obtained from original land surfaces may provide reliable ages. Since such material immediately pre-dates an eruption it should be preferable to material which post-dates one by an indeterminate period.

*Regional volcanic activity*

Recent determinations of the ages of several regional volcanoes considered to be "young" have shown them to be older, or potentially older, than previously thought. The studies have involved a range of techniques - radiocarbon dating of material in palaeosols and lake cores, thermo-luminescence dating of quartz grains in sands, palaeo-magnetism, and exposure dating of basalts using chlorine - 36. The majority of published ages for the Mt Gambier complex, derived from radiocarbon dating (Fergusson & Rafter 1957, Blackburn et al. 1982), palaeomagnetism (Barbetti and Sheard 1981) and thermoluminescence (Robertson et al. 1996) of tuff deposits and associated organic material, fall between 4 and 5ka, but radiocarbon dating of a Blue Lake sediment core suggests a very much older date of about 31ka (Leaney et al. 1995). It is considered possible by that the younger dates derive from renewed volcanic activity in the area that included the formation of Mt Schank. A cosmogenic chlorine-36 exposure age (32 ka) for the Harman Valley basalt flow from Mt Napier is consistent with the younger carbon-14 age found by Head et al. (1991) for overlying swamp sediments (Stone et al. 1997). An age for the Mt Eccles volcano is based on limits established by the age of peats in swamps formed when its lava blocked drainage channels and the age of older Mt Napier basalts on which these deposits sit (Stone et al. 1997). Mt Schank, and possibly Mt Gambier, are the youngest volcanoes on the Newer Basalt volcanic plain.

Interestingly, at least three volcanoes have given ages in the range 30 - 35ka BP – Tower Hill, Mt Eccles and Mt Napier (Table 2). It is possible that the closeness of these eruptions is due to a localised increase in mantle convective activity or crustal tectonic activity. Stone et al. (1997) have pointed out that the excellent preservation of volcanic features in these volcanoes and the failure of blocked streams to re-establish their courses, while originally suggestive of a young age for these volcanoes, may instead be due to extended periods of aridity.

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